Performance Evaluation of Median U-Turn Intersection for Alleviating Traffic Congestion: An Agent-Based Simulation Study

Md Mamunur Rahman, Yuan Zhou, Jamie Rogers
Department of Industrial, Manufacturing and Systems Engineering
The University of Texas at Arlington
TX 76019, USA

Abstract

In recent years, urban mobility has become a big concern for Dhaka city, the capital of Bangladesh, due to severe traffic congestion. At-grade signalized intersections are one of the bottlenecks that significantly affect the capacity of the urban road network resulting in long waiting time and disrupted traffic flow. In this article, we studied the performance of Median U-Turn (MUT) intersection, a nonconventional low-cost design, as an alternative to the traditional four-way intersection. A high-fidelity simulation model was developed using the Agent-Based Modeling (ABM) approach to mimic the traffic flow of one of the busiest intersections in Dhaka city. Data were collected from a field survey during morning peak hours. The simulation results show that the average travel time to cross the intersection can be decreased by 16.8% by implementing MUT intersection, although the average number of stops increases by 5.5% in comparison to the existing traditional four-way intersection. Overall, the composite performance metric shows an improvement of 14.3%. Additional simulation experiments reveal that the performance of MUT intersection is comparatively better in case of moderate to high traffic volumes than low traffic volumes. The findings of this study provide valuable evidence to the transport planners to consider MUT at busy intersections for alleviating traffic congestion in Dhaka city.

Keywords
Median U-Turn, Four-Way Intersection, Traffic Congestion, Agent-Based Modeling, Dhaka City.

1. Introduction

Dhaka, the capital city of Bangladesh, is one of the topmost densely populated cities in the world. To meet the travel demand, 139,748 new traffics are hitting the roads of Dhaka every year, though the capacity of the roads remains almost the same [1, 2]. Therefore, the city is distressed by terrible traffic congestion resulting in a sharp drop of average traffic speed from 17 kilometer per hour (km/hr) to 8 km/hr during the past ten years [3]. Every year the economy is incurring a loss of 2.68 billion US dollar due to this heavy traffic congestion [3]. Although the government has taken initiatives to build flyovers in some of the important intersections to improve the traffic condition, this expensive solution is not always feasible for many locations [4, 5]. Previously, several studies [6–12] have been done for the alleviation of traffic congestion in Dhaka city, but none of these studies considered the impact of unconventional intersection design. In this study, we will investigate the effectiveness of Median U-Turn (MUT), a relatively low-cost unconventional intersection, as an alternative to the signalized four-way intersection for the alleviation of traffic congestion.

2. Methodology
2.1 Data Collection

The intersection between the roads Dhaka-Mymensing Hwy and Sonargaon Janapath at House-Building, one of the busiest intersections in Dhaka city, was selected for this study. A field survey was conducted to capture the traffic characteristics at the intersection using video cameras. Later, the recorded videos were played to count the traffic volumes, types of vehicles, and their turning behaviors in different directions. The survey was done from 7:00 am to 10:00 am, morning peak hours, under normal weather conditions on weekdays. The major road, Dhaka-Mymensing Hwy, is an eight-lane median divided road with a lane width of 3.6 meters and the minor road, Sonargaon Janapath, is a four-lane median divided road with a lane width of 3.0 meters. The direction of the traffic flow is left hand. Figure 1 shows the hourly traffic volumes in different directions and traffic signal phase diagram.
2.2 Median U-Turn Intersection

Figure 2 illustrates a Median U-Turn (MUT) as an alternative to the conventional four-way intersection. There are two traffic signal lights at the two median openings (left and right) and one traffic signal light at the main intersection.

No vehicle is allowed to make a right turn at the main intersection. The drivers intended to make a right turn at the intersection will make a left turn first, then approach to the storage bay, and finally make a U-turn to reach their destinations. In case of low traffic volumes, the two traffic signals at the median openings can be eliminated. In that case, the vehicles waiting at storage bay will give yield to the vehicles on the main street. The traffic signal light at the main intersection has got only two phases as opposed to four which is common for traditional four-way intersection (see Figure 1b).

2.3 Agent-Based Modeling

A microscopic traffic simulation model is developed using the Agent-Based Modeling (ABM) technique, an emerging computational modeling paradigm that has received significant interest among the researchers in recent years. As opposed to the traditional top-down modeling approach, ABM is a bottom-up modeling technique where the agents act like intelligent autonomous entities which can assess the situation, make interactions among themselves, and make
decisions based on the predefined set of rules. Figure 3 shows an overview of the agents in the simulation model design. In the simulation model, every vehicle is represented by an individual autonomous agent that is governed by a set of attributes and predefined behavior rules. Vehicles’ attributes those remain unchanged throughout the simulation, e.g., length and width of the vehicles, are fixed attributes whereas the values of the dynamic attributes change over time during the simulation process, e.g., speed, acceleration, and deceleration. Besides, the agents interact with the environment which contains roads, intersections, traffic lights, traffic signs, and so on. AnyLogic® (University Researcher edition 8.3.3), a widely used Java-based Agent-Based Modeling software, is used to develop the simulation model for the baseline scenario and to perform experimentations.

**Agents**

- Passenger car
- Public bus
- Motorcycle
- Micro bus
- Station wagon
- Taxi
- CNG auto rickshaw
- Human hauler
- Pickup truck
- Heavy duty truck

**Environment**

- Road
- Intersection
- Median
- Traffic light
- Traffic sign

Figure 3: An overview of the agents in the simulation

### 2.4 Measures of Effectiveness

In this study, vehicle average travel time and the average number of stops to cross the intersection are used as the measures of effectiveness (MOE). Average travel time and the average number of stops are computed using equation 1 and 2, respectively.

\[
T = \frac{1}{N} \sum_{i=1}^{N} (t_i' - t_i) \quad (1)
\]

\[
S = \frac{1}{N} \sum_{i=1}^{N} n_i \quad (2)
\]

Where, \(T\) - average travel time, \(S\) - average number of stops, \(N\) - number of vehicles discharged from the simulation, \(t_i\) - entry time of vehicle \(i\) in the simulation, \(t_i'\) - exit time of vehicle \(i\) from the simulation, and \(n_i\) - number of stops by vehicle \(i\) to cross the intersection.

**Algorithm 1**: Total number of stops calculation algorithm

1. **Start**
2. Vehicle ← [vehicle 1, vehicle 2, …, vehicle \(N\)]  // \(N\) is the number of vehicles on the road at that moment
3. for \(j \leftarrow \) Vehicle do
4. \(V \leftarrow \) Get Vehicle Speed in foot per second
5. if \(V \geq 15\) do
6. \(\text{Flag} \leftarrow \text{true}\)
7. end if
8. if \((V < 10 \text{ AND} \text{Flag} == \text{true})\) do
9. \(\text{Stop} \leftarrow \text{Stop} + 1\)
10. \(\text{Flag} \leftarrow \text{false}\)
11. end if
12. end for
13. **Stop**

A stop is counted if the speed of a vehicle falls below 10 feet per second (fps) [13]. To generate additional stops for a stopped vehicle, its speed must reach again minimum 15 fps [13]. Therefore, multiple stops will not be counted for a vehicle moving up in a queue. We developed algorithm 1 to calculate the total number of stops. To implement the algorithm in AnyLogic®, two variables, \(V\) and \(\text{Flag}\), are defined under the agent class and another variable, \(\text{Stop}\) is defined under the Main class. Then, an event is created under the Main class and the algorithm is executed every second as the action of the event. Finally, at the end of the simulation, equation 2 is utilized to calculate the average number of stops per vehicle.
2.5 Simulation Experiments
Table 1 shows the overview of the simulation experiments with an hourly volume of the traffics in different directions. Baseline scenario depicts the morning peak hours traffic volume that we got from the field survey. Scenario 1 represents a moderate traffic volume and scenario 2 represents a low traffic volume which are 50% and 30% of the baseline scenario, respectively. The ratio of the turning movements and through traffics at the intersection are kept identical for all the scenarios.

![Table 1: Design of the simulation experiments](image)

2.6 Simulation Replications
The developed simulation model is stochastic in nature and a certain disparity of the simulation results is apparent for different random seed number. Equation 3 is used to compute the tolerance value of the MOEs for a given number of simulation replication [14]. For example, in case of baseline scenario, the estimated tolerance values for 20 replications are 1.37% and 1.15% for the average travel time and the average number of stops, respectively, at 0.05 level of significance. The estimated tolerance values of the both MOEs derived from the three scenarios are below 5%, our acceptable maximum limit. Therefore, we set 20 replications for each scenario.

\[
d_n = \frac{t_{n-1,\alpha/2} \times S_n/\sqrt{n}}{\bar{X}_n}
\]

Where, \( n \) - number of replications, \( d_n \) - desired tolerance as a fraction of the sample mean, \( t_{n-1,\alpha/2} \) - critical value of the Student’s t-distribution, \( \alpha \) - level of significance, \( S_n \) - sample standard deviation, and \( \bar{X}_n \) - sample mean.

2.7 Optimization of Traffic Signal Timing
There is an inverse relationship between waiting time at the intersection and number of stops. Shorter traffic signal cycle length reduces waiting time at the intersection but increases the number of stops and longer cycle length results the opposite. Moreover, the two MOEs are non-commensurable, one is relatively smaller than the other one. Therefore, for optimization, a single objective function is formed by combining the two MOEs using equation 4. In the composite performance metric, every additional stop penalizes \( k \) seconds of delay to the travel time. In this study, we considered the value of \( k \) as 20 seconds as per the recommendation of previous studies [15]. A smaller composite objective value indicates better performance.

\[
\text{Composite objective} = \text{Travel time} + (k \times \text{Number of stops})
\]
3. Results and Discussion

Table 2 summarizes the simulation outputs based on 20 replications for each scenario. To examine whether there is a significant difference in the mean MOEs between the conventional intersection and MUT, the independent two-sample t-test is conducted for the below hypothesis.

Null hypothesis \((H_0)\) : The difference between the mean values of conventional and MUT intersection is zero

Alternative hypothesis \((H_1)\) : The difference is not zero

Table 2: Summary of the simulation results

<table>
<thead>
<tr>
<th>Intersection type</th>
<th>Scenarios</th>
<th>Travel time (seconds)</th>
<th>Number of Stops</th>
<th>Composite objective (seconds)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Mean</td>
<td>SD</td>
<td>Mean</td>
</tr>
<tr>
<td>Conventional</td>
<td>Baseline scenario</td>
<td>312.13</td>
<td>9.15</td>
<td>2.01</td>
</tr>
<tr>
<td></td>
<td>Scenario 1</td>
<td>168.58</td>
<td>16.14</td>
<td>1.22</td>
</tr>
<tr>
<td></td>
<td>Scenario 2</td>
<td>101.30</td>
<td>4.16</td>
<td>0.88</td>
</tr>
<tr>
<td>Median U-Turn</td>
<td>Baseline scenario</td>
<td>259.68</td>
<td>5.75</td>
<td>2.12</td>
</tr>
<tr>
<td></td>
<td>Scenario 1</td>
<td>122.83</td>
<td>7.50</td>
<td>1.48</td>
</tr>
<tr>
<td></td>
<td>Scenario 2</td>
<td>93.85</td>
<td>1.93</td>
<td>0.92</td>
</tr>
</tbody>
</table>

Note: SD - Standard Deviation

Table 3: Summary statistics of t-test for two independent means

<table>
<thead>
<tr>
<th>Scenario</th>
<th>MOE</th>
<th>Null hypothesis ((H_0))</th>
<th>t-value</th>
<th>P-Value</th>
<th>Decision</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline scenario</td>
<td>Travel time</td>
<td>(\mu_{\text{Conventional}} - \mu_{\text{MUT}} = 0)</td>
<td>21.7</td>
<td>&lt; 0.0001</td>
<td>Reject (H_0)</td>
</tr>
<tr>
<td></td>
<td>Number of stops</td>
<td>(\mu_{\text{Conventional}} - \mu_{\text{MUT}} = 0)</td>
<td>-7.59</td>
<td>&lt; 0.0001</td>
<td>Reject (H_0)</td>
</tr>
<tr>
<td></td>
<td>Composite objective</td>
<td>(\mu_{\text{Conventional}} - \mu_{\text{MUT}} = 0)</td>
<td>21.38</td>
<td>&lt; 0.0001</td>
<td>Reject (H_0)</td>
</tr>
<tr>
<td>Scenario 1</td>
<td>Travel time</td>
<td>(\mu_{\text{Conventional}} - \mu_{\text{MUT}} = 0)</td>
<td>11.99</td>
<td>&lt; 0.0001</td>
<td>Reject (H_0)</td>
</tr>
<tr>
<td></td>
<td>Number of stops</td>
<td>(\mu_{\text{Conventional}} - \mu_{\text{MUT}} = 0)</td>
<td>-6.61</td>
<td>&lt; 0.0001</td>
<td>Reject (H_0)</td>
</tr>
<tr>
<td></td>
<td>Composite objective</td>
<td>(\mu_{\text{Conventional}} - \mu_{\text{MUT}} = 0)</td>
<td>9.48</td>
<td>&lt; 0.0001</td>
<td>Reject (H_0)</td>
</tr>
<tr>
<td>Scenario 2</td>
<td>Travel time</td>
<td>(\mu_{\text{Conventional}} - \mu_{\text{MUT}} = 0)</td>
<td>7.26</td>
<td>&lt; 0.0001</td>
<td>Reject (H_0)</td>
</tr>
<tr>
<td></td>
<td>Number of stops</td>
<td>(\mu_{\text{Conventional}} - \mu_{\text{MUT}} = 0)</td>
<td>-2.93</td>
<td>0.0057</td>
<td>Reject (H_0)</td>
</tr>
<tr>
<td></td>
<td>Composite objective</td>
<td>(\mu_{\text{Conventional}} - \mu_{\text{MUT}} = 0)</td>
<td>5.48</td>
<td>&lt; 0.0001</td>
<td>Reject (H_0)</td>
</tr>
</tbody>
</table>

Note: The p-values are computed for two-tailed hypothesis test

According to the t-tests results presented in Table 3, null hypotheses for all the scenarios are rejected at 0.01 level of significance. Therefore, the true means of the MOEs are different for the conventional and MUT intersection. Table 4 shows the comparisons of the MOEs between the conventional and MUT intersection. For all the scenarios, it is apparent from the table that the average travel time reduces in MUT intersection, although the average number of stops increases. However, the performance of the MUT intersection is always higher with respect to the composite
objective. Another important finding is that the MUT performs better for medium to high traffic volumes compared to low traffic volume.

Table 4: Comparison of the MOEs between MUT and conventional four-way intersection

<table>
<thead>
<tr>
<th>Scenarios</th>
<th>Travel time (seconds)</th>
<th>Number of Stops</th>
<th>Composite objective (seconds)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline scenario (Heavy traffic volume)</td>
<td>16.80% ↓</td>
<td>5.47% ↑</td>
<td>14.26% ↓</td>
</tr>
<tr>
<td>Scenario 1 (Moderate traffic volume)</td>
<td>27.14% ↓</td>
<td>21.40% ↑</td>
<td>20.99% ↓</td>
</tr>
<tr>
<td>Scenario 2 (Low traffic volume)</td>
<td>7.35% ↓</td>
<td>4.94% ↑</td>
<td>5.53% ↓</td>
</tr>
</tbody>
</table>

Note: ↑ - increase; ↓ - decrease

4. Conclusion
In this study, the performance of MUT intersection is evaluated for one of the busiest intersections in Dhaka city based on real data for different traffic scenarios. According to the simulation results, MUT intersection can help to alleviate traffic congestion significantly for medium to high traffic volume situations. However, further research is recommended to examine whether the small improvement of the performance in case of low traffic volume situations justifies the MUT implementation cost.

References